International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 13, No. 2, June 2022, pp. 744~754
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v13.i2.pp744-754

Comparison between matrix and back-to-back converter in flywheel energy storage systems

Nguyen Hung Do[1,2], Sy Manh Ho[1], Quoc Tuan Le[1], Tung Hoang[1], Trong Minh Tran[1], Phuong Vu[1]
[1]School of Electrical and Electronic Engineering, Hanoi University of Science and Technology, Hanoi, Vietnam
[2]Department of Electrical, Ha Noi Polytechnic Collage, Hanoi, Vietnam

Article Info

Article history:

Received Sep 28, 2021
Revised Feb 26, 2022
Accepted Mar 11, 2022

Keywords:

Aaxial flux permanent magnet
Back-to-back converter
Flywheel energy storage system
Matrix converter

ABSTRACT

Flywheel energy storage systems (FESS) are considered as the grid integration of renewable energy sources due to their buit-in advantages such as fast response, long cycle life and flexibility in providing auxiliary services to the grid, such as frequency regulation, and voltage support. This paper introduces the structure and comparison results of matrix converter and back-to-back converter which integrated with axial flux permanent magnet motor (AFPM) in FESS. Two converters are functionally equivalent in terms of input power quality and energy regeneration capabilities but need to be compared in terms of performance testing with speed response. In this paper, the research results have been verified that matrix converters perform more effective than back-to-back converters.

Corresponding Author:

Phuong Vu
School of Electrical and Electronic Engineering, Hanoi University of Science and Technology
No. 1, Dai Co Viet Road, Hai Ba Trung, Hanoi, Vietnam
Email: phuong.vuhoang@hust.edu.vn

1. INTRODUCTION

Flywheel energy storage system (FESS) is a clean and efficient method to level supply in consequence demanding in energy grids [1], [2]. In FESS, electrical energy is stored as kinetic energy of the flywheel. The stored energy in FESS depends on the flywheel structure (inertia) and rotation mass's speed. The inertia allows the rotor to continue rotating and kinetic energy is converted into electricity. The large number of modern high-speed coil energy storage systems include a large rotating cylinder (a rim attached to a shaft) that is supported on a stator by magnetic prismatic bearings [3]. This makes the flywheel system to reduce frictional forces and maintain performance. FESS is connected to an engine or generator to exchange the grid through electronics. On account of this, FESS can bridge the gap between short-term power and long-term energy storage with optimum load and circulation characteristics. Moreover FESS systems have high energy density as well as a high efficiency [4], [5]. In addition, their response time is fast, making it ideal for applications that require a large capacity to be mobilized in a short period of time charge/discharge capacity: high speed, not affected by temperature or deep discharge DoD as with using batteries [6]. On the other hand, the flywheel has a long life that is almost independent of the charge and discharge cycles. Remarkably, it is an efficient energy storage system that is also very environmentally friendly. In particular, the system emits low levels of pollution, does not require routine maintenance and the materials used in its construction are not as harmful to the environment as batteries. The disadvantage is that a potential safety risk arises if a flywheel is loaded with more energy than its components can handle. FESS not only is more expensive than other energy storage but also has challenges in minimizing energy loss due to friction [7]. Moreover, traditional bearings are inefficient, so magnetic bearings are the current trend. Notwithstanding, this is still a trend in the field of energy storage, and researchers are paying close attention to it.

Axial flux permanent magnet motors (AFPMs) are major components in FESSs, which helps the two-way energy exchange between dynamic energy and electrical energy. AFPM motor in have higher air-gap flux density, power density and torque density than directional flux permanently synchronous motors [8]–[10]. This leads to the motor structure more compact, use less core material. In addition, noise and vibration during operation are lower during operation is lower than traditional radial flux permanent magnet machines [11]. Because of the unique disk structure, AFPM is an excellent choice for FESS applications. The characteristics of AFPM motor belong to the type of permanently synchronous motor, so the efficiency is higher, the loss on the rotor winding is less than that of the asynchronous motor [12], [13]. To exchange energy between flywheel and the power system, a converter is adopted as an interface. The converters assist in the transformation of voltage when changing motor speed and in the conversion energy while the motor feedbacks capacity to the grid [14]. The common used configuration is AC-DC-AC (back-to-back) or matrix converter. Both converters accommodate bidirectional energy exchange between the grid and the flywheel in FESS.

Matrix converters supply bi-directional power flow, sinusoidal input/output waveforms, and controllable input power factor. These being the cases, matrix converters have received considerable attention in recent years. They may also prove to be a viable alternative to back-to-back converter. The matrix converters have already been compared to the back-to-back converter, with some promising but equivocal results. Due to the enormous number of system characteristics (input filter and load parameters, switching frequency, output frequency, modulation methods, etc. and inherent differences between the two converter topologies, such as the maximum voltage transfer ratio, the comparison is extremely difficult.

In this paper the comparison between back-to-back and matrix converters is performed by evaluating the maximum output power that each converter can deliver to the load for different output frequencies. The main comparison has been performed for different values of: speed and motor torque response; power and energy response. The paper is organized as follows. The structure of matrix and back-to-back converter in FESS using AFPM motor is presented in section 2 and their comparison is shown in section 3. The simulation results are given in section 4. Finally, some concluding remarks are stated in section 5.

2. MODELING OF MATRIX AND BACK- TO- BACK CONVERTER IN FESS USING AFPM

2.1. Mathematical model of AFPM

The flux linkage in any winding is the summation of its self inductances and mutual inductances caused by other currents. The voltage equations for the AFPM machine can be written as [5], [15]:

$$\begin{cases} u_a = R_s i_a + \frac{d\phi_a}{dt} \\ u_b = R_s i_b + \frac{d\phi_b}{dt} \\ u_c = R_s i_c + \frac{d\phi_c}{dt} \end{cases} \tag{1}$$

where R_s is the stator resistance and i_k, ϕ_k, u_k are respectively the current, flux and reference voltage from the magnet to the stator. Consider that the coordinate axis dq rotates in the rotor direction and the rotor radial coincides with the rotor radial axis. Equation for magnet flux along the dq axis:

$$\begin{cases} \phi_d = L_d i_d + \phi_{PM} \\ \phi_q = L_q i_q \end{cases} \tag{1}$$

where L_d and L_q are the direct and the quadrature axis inductances, ϕ_{PM} is the amplitude of the flux and i_d, i_q are the direct and quadrature currents in the d-q reference frame. Voltage equation on the dq axis [5] [16]:

$$\begin{cases} u_d = L_d \frac{di_d}{dt} + R_s i_d - \omega_e L_q i_q \\ u_q = L_q \frac{di_q}{dt} + R_s i_q + \omega_e L_q i_q + \omega_e \phi_{PM} \end{cases} \tag{3}$$

where $\omega_e = p\omega_r$ is the electrical speed of the rotor. Instantaneous active power of machine:

$$P = ui = u_a i_a + u_b i_b + u_c i_c \tag{4}$$

applying the Park transformation:

$$T_e = \rho \frac{P_{ele}}{\omega_e} = \frac{3}{2}\rho(L_d - L_q)I_d I_q + \phi_{PM} I_q \quad (5)$$

$$P = \frac{3}{2}(u_d i_d + u_q i_q) \quad (6)$$

$$P_{ele} = \frac{3}{2}\omega_e(L_d I_d I_q - L_q I_q I_d - \phi_{PM} I_q) = \frac{3}{2}\omega_e(L_d(I_d I_q - I_q I_d) - \phi_{PM} I_q) \quad (7)$$

where T_e is the electromagnetic torque**,** ρ is the mass density of the flywheel. The kinetic equations:

$$T_e - T_l - J\frac{d\omega_r}{dt} = 0; \frac{d\omega_r}{dt} = \frac{T_e - T_l}{J}; \omega_r = \frac{1}{Js}(T_e - T_l) \quad (8)$$

where T_l is load torque, J is the moment of inertia. Figure 1 shows the model structure of the AFPM motor in MATLAB. The model consists of a three-phase electric part to generate three-phase current, an electromechanical part to generate electromagnetic torque and a mechanical part to produce the motor speed.

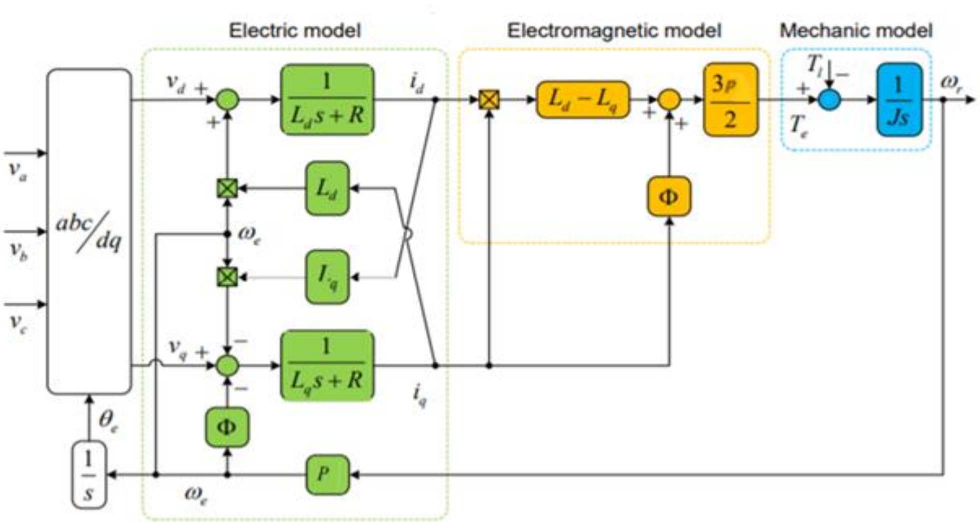


Figure 1. Modeling AFPM

2.2. Controller structure of the converters in FESS

In this paper, a comparison is made between two power electronic converters that are matrix converters (MC) and back-to-back for FESS using AFPM motors. The main advantage is that both converters are responsive to two-way energy exchange in the flywheel energy storage system. The matrix converter uses two-way semiconductor valves, with control algorithms that make high efficient two-way energy exchange. Meanwhile, the back-to-back converter consists of the AC/DC and DC/AC converters linked together via the DC bus. The semiconductor valves are controlled by a spatial vector modulation algorithm that reduces current harmonics.

2.2.1. Modulation method in matrix converter

The purpose of the modulation method is to create a sinusoidal three-phase output voltage system, and the input dissipation current is also sinusoidal with an adjustable phase angle to the input voltage. The amount set for the modulation scheme is the output voltage and the phase angle of the input current [17]. The modulation rule for structure of matrix converter as in Figure 2.

The modulation rule includes the following steps:

Step 1: determine the position of the desired output voltage vector and input current vector on the coordinate plane in the hexagons.

Step 2: calculate the relative energizing time of the vectors used d_1, d_2, d_3, d_4, d_0, according to the formula [18], [19].

$$\begin{cases} d_1 = m\sin\Delta_0 \sin(\frac{\pi}{3} - \Delta_i) \\ d_2 = m\sin\Delta_0 \sin\Delta_i \\ d_3 = m\sin(\frac{\pi}{3} - \Delta_0)\sin(\frac{\pi}{3} - \Delta_i) \\ d_4 = m\sin(\frac{\pi}{3} - \Delta_0)\sin\Delta_i \end{cases} \quad (9)$$

and d_0 is written as:

$$d_0 = 1 - (d_1 + d_2 + d_3 + d_4) \quad (10)$$

where m is the modulation index (0<m<1). Δ_o is the angle formed by the vector of desired output voltage and the bisector of the sector in which it's located, Δ_i is the angle formed by the vector of desired input current and the bisector of the sector in which it's located.
Step 3: select valve combinations and the order of execution of the standard vectors used in a logical sequence [20].
Step 4: output the control signals to the external circuit.

Internal current loop circuit includes two independent PI controllers, controlling two DC current components i_{sd} and i_{sq}, responsible for calculating voltage components u_{sd} and u_{sq} as output quantities of the two sets. PI. To ensure no interaction between the d-axis and q-axis components, we have the structure of the current controller as shown in Figure 3. The external speed loop controls the motor speed according to the set speed value using the PI controller as in Figure 4.
P_c: : the number of pole pairs
ψ_p : rotor flux.

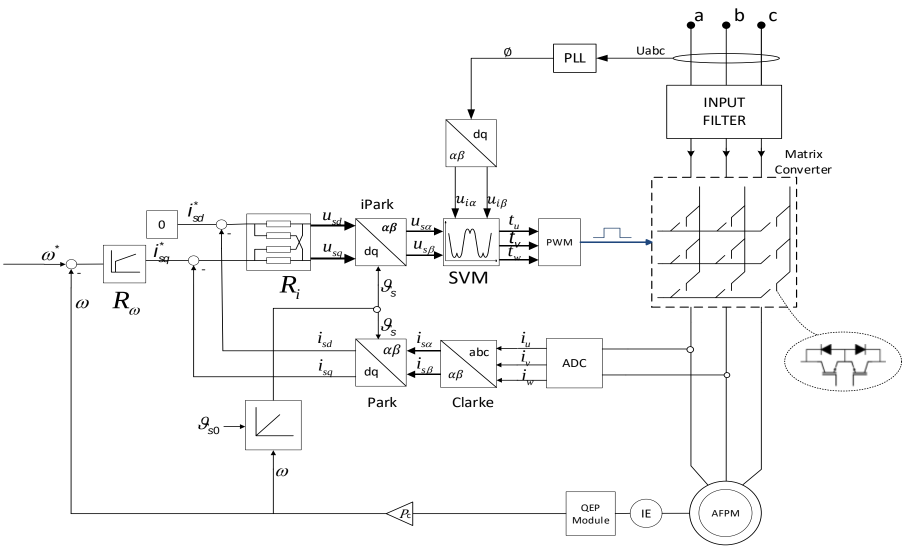


Figure 2. Structure of MC in FESS

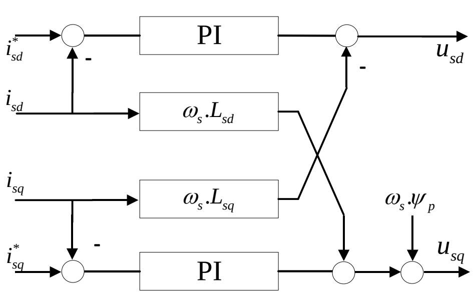


Figure 3. The control structure of the current controller

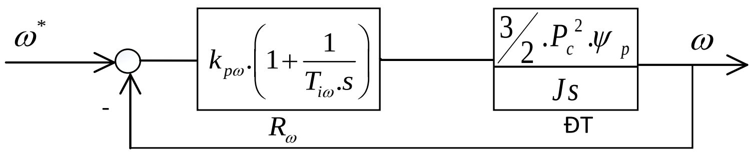


Figure 4. The structure of the rotational speed controller

2.2.2. Modulation method in back-to-back converter

The three-phase AC/DC/AC converters, also known as the back-to-back converters, consists of two AC/DC and DC/AC converters linked together by a DC bus. The semiconductor valves are controlled by the SVM algorithm to reduce current harmonics as shown in Figure 5. The AC/DC converter works on the principle of an active rectifier. The main task of the active rectifier controller is to keep the DC voltage value Udc close to the set value Udc_ref and stable under ideal conditions as in Figure 6. In addition to meet the grid connection condition, use the PLL phase-locked loop calculate the exact amount of modulation current and voltage. The DC and current side voltage regulators are PI regulators. Through the voltage regulator on the DC side, we will get the input current value of the current regulator as I_{d_ref}, I_{q_ref} is taken to be zero under ideal conditions.

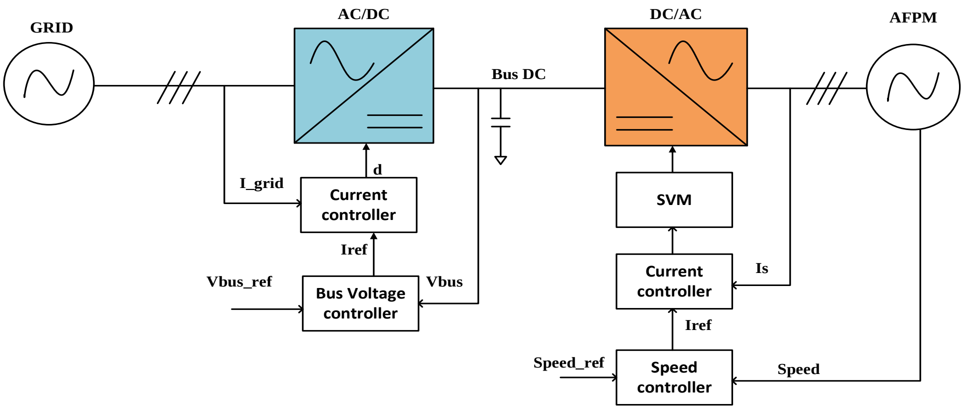


Figure 5. Back-to-back structure in FESS

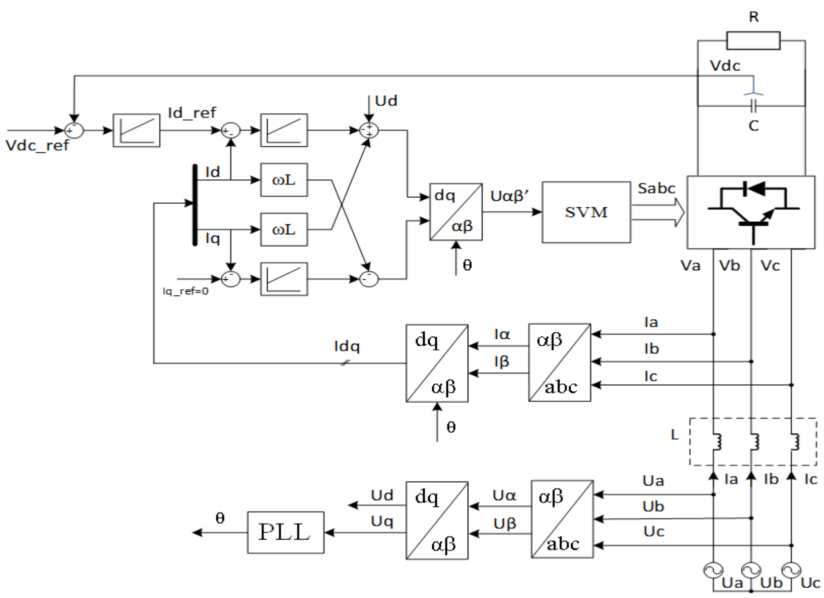


Figure 6. Active rectifier control structure

3. STRUCTURE COMPARISION OF BACK-TO-BACK AND MATRIX CONVERTER IN FESS USING AFPM MOTOR

The back-to-back converters have the advantages of simple control structure, the bonding capacitor acts as an energy storage element and helps to keep the DC voltage constant on the DC bus. This is meant for AC-AC conversion applications that require internal energy accumulation due to high load dynamics. But these converters have some disadvantages because it has DC capacitors, so the kinematics of the back-to-back converter is slower than that of the MC due to the lack of DC Link capacitors. The input current due to this diode rectifier produces greater distortion. The output voltage communication inverter has only 3 levels +Udc, 0, -Udc, while the output voltage matrix converter is modulated according to the input voltage. Because the spatial vector modulation algorithm is used, the maximum output voltage limit is 86.6% of the input voltage. The requirement an efficient FESS system is high power density. However, back-to-back converters use more passive elements than matrix converters, resulting in larger converter sizes, which reduces system power density [21]. Figure 7 shows the structure of the matrix converter.

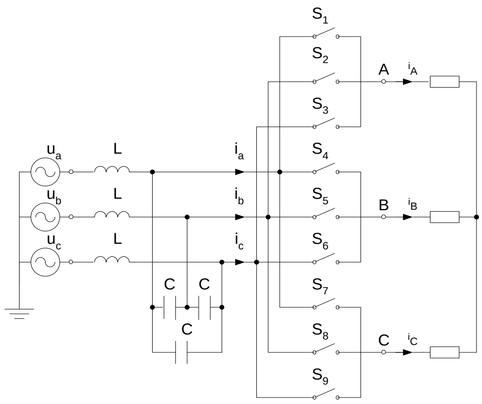


Figure 7. Diagram of the matrix converter

AC-AC switching implementations have need of internal energy storage due to high load dynamics, the ability to extend or compensate for resistance capacity is not limited. Therefore, the matrix frequency variable does not provide the most appropriate solution because it does not contain the energy storage component DC-link capacitors. In addition, for the matrix converter, since there is no reverse diode path, the bidirectional energy exchange must be actively imposed by the valve control algorithm. The dynamics of matrix converters are faster than back-to-back converters due to the lacking of DC-link condenser components. This will meet the requirement in the flywheel energy storage system that is the ability to mobilize instantaneous power. In addition, the more compact structure of the matrix converter in comparison to back-to-back converter is also an advantage that enhances the power density of the flywheel energy storage system.

Any other way, the matrix converters have a number of outstanding features such as being able to generate a sinusoidal output voltage with variable amplitude and frequency, sinusoidal input current, a power factor of 1, applicable to all power ranges from small to large [22]. Compared with other converters, the matrix converter has the advantage of a higher power-to-mass ratio as well as a higher power-to-volume ratio. In addition, the power electronic part is completely using semiconductor elements, so the matrix converter has higher tolerance temperature, high reliability, long life and significantly reduced size. The ability to work in all four quadrants without the need for additional components along with the compact size makes it possible to integrate the frequency converter with the motor, creating a unified drive system. Matrix converters have higher performance and quality than back-to-back converter [14], [23], [24]. But the technique to control the opening and closing of the valves is much more convoluted due to the use of 9 two-way valse. Compared to back-to-back converter, it is more difficult to modulate the switches in matrix converter because three variable input voltages can be used for modulation.

The output voltage of the matrix converter must be modulated straight from the inpute voltage. The waveform of the output voltages are synthesized by sequentially sampling one of input voltages. The sampling rate must be set substantially higher than both the input and output frequencies, and the duration of each sample is controlled so that the average value of the output waveform in each sample cycle follows the

waveform desired output. In addition, the matrix converter also needs to use additional input filters to improve control quality.

4. PERFORMANCE COMPARISON

4.1. Simulation setup

Change the motor speed according to different working modes of the energy storage system using the flywheel. Measure the power received from the grid and the power that the system pushes to the grid after the storage process. Then evaluate the power mobilization of the system when using two power converters. Simulation scenario as in Figure 8. Table 1 shows AFPM datasheet.

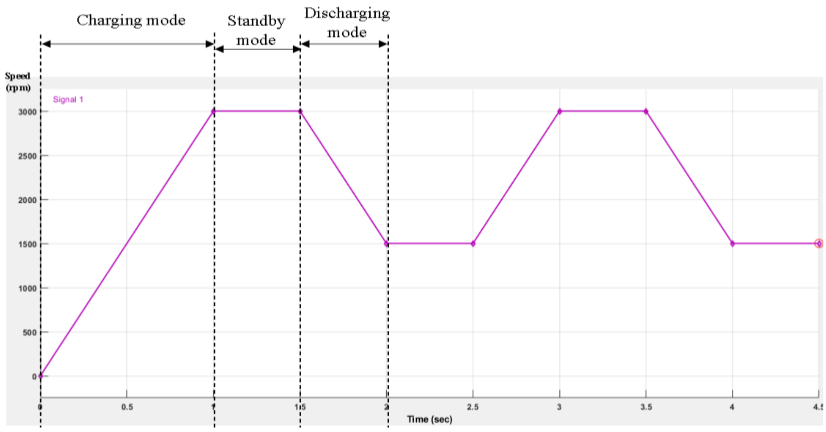


Figure 8. Diagram of motor speed setting

Table 1. AFPM datasheet

Motor parameters	Value
Stator resistance	Rs = 5Ω
Armature inductance	Lsd = Lsq = 0.0039H
The number of pole pairs	Pc = 2
Magnetic flux	Flux = 0.5048T
Moment of inertia	J = 0.0185 kg.m^2

4.2. Results and discussion

4.2.1. Speed response comparison

The simulation results of back-to-back converter and matrix converter are shown in Figure 9 and 10 respectively. In this case, using both converters give the engine speed line close to the set speed. And there is almost no adjustment in the operating modes of the system when simulating with both converters.

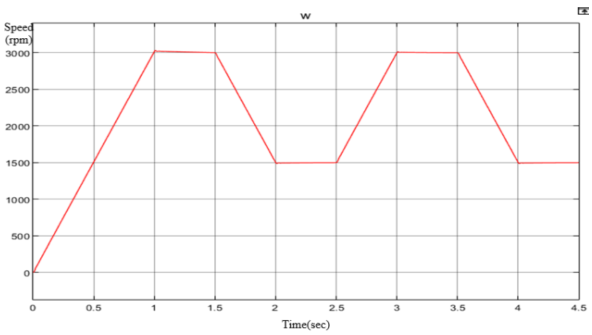


Figure 9. Graph of speed response using back-to-back

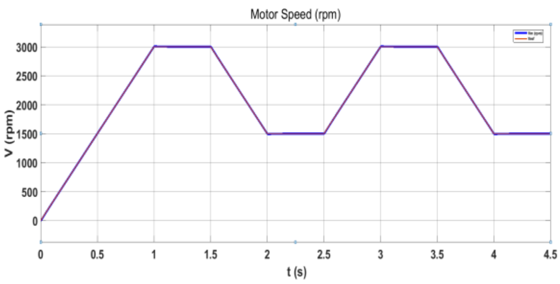
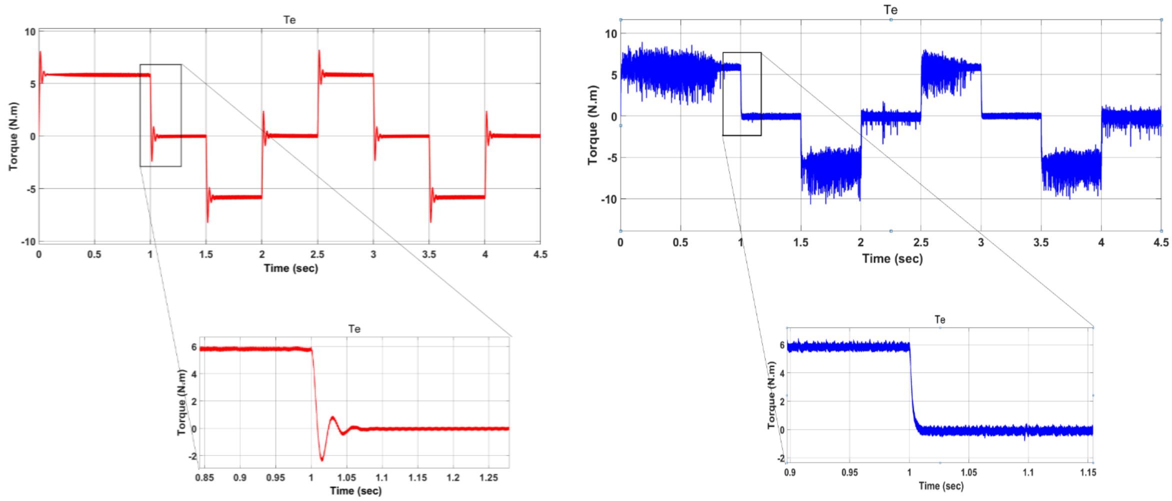


Figure 10. Graph of speed response using matrix converter

4.2.2. Motor torque response comparison

The simulation results of back-to-back converter and matrix converter are shown in Figure 11 (a) and Figure 11 (b) respectively. When starting standby mode at 1s, the matrix converter has a faster charge-to-steady-state time than back-to-back converter. But compared to back-to-back converter, the resulting torque of the matrix converter has a higher pulse rate.



(a) (b)

Figure 11. Graph of torque response: (a) back-to-back (left) and (b) matrix converter (right)

4.2.3. Power response comparison

Evaluation of responsiveness pushing power to the grid as demonstrated in Figure 12 and Figure 13. The power wasted in standby mode are loss components that gradually decrease stored energy when the system is in standby mode of operation. The power wasted in standby mode are regulated by the flywheel design and are typically caused by friction, aerodynamic drag, and open-circuit engine/generator losses that slow down the rotor. Vacuum containment and magnetic bearings are commonly used to reduce standby power losses [25], [4]. Standby losses should be kept to a minimum, typically less than 25 W/kWh of stored energy and within 1-2 percent of power output. Using a back-to-back converter, the power pushed to the grid responds more slowly than when using a matrix converter.

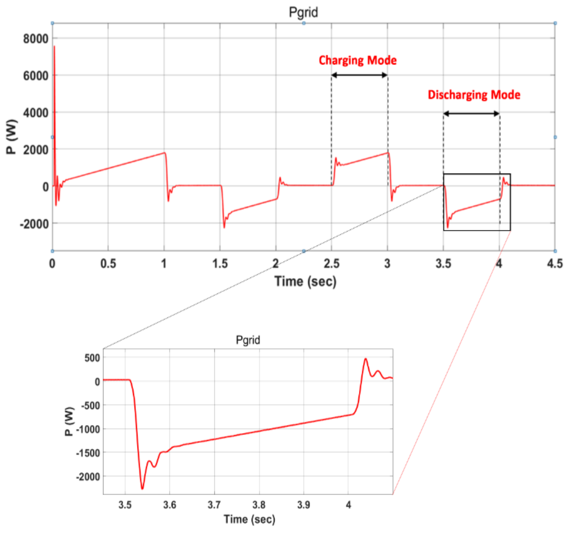


Figure 12. Graph of power response using back-to-back

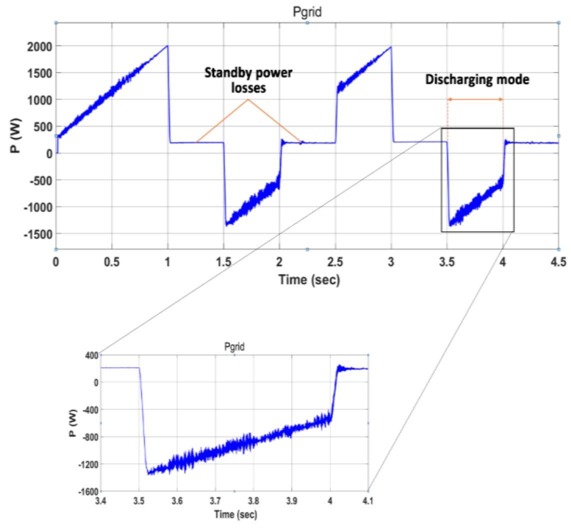


Figure 13. Graph of power response using matrix converter

4.2.4. Energy response comparison

In charging mode, simulation results of back-to-back as in Figure 14 (a) and matrix converter as in Figure 14 (b) (seen in Appendix) show that matrix converter has faster charge-to-steady-state time than back-to-back converter. In power charging mode, the system gets power from the grid, engine speed increases to 3000 rpm and E also increases to 900 (J). In standby mode, engine speed unchanged at 3000 rpm, the system no longer mobilizes much power from the grid and mainly to maintain engine speed and E remains 900 (J). In energy discharge mode, engine speed is reduced, the system starts to push power to the grid for a period of 0.5 s and the energy stored in the system also decreases gradually.

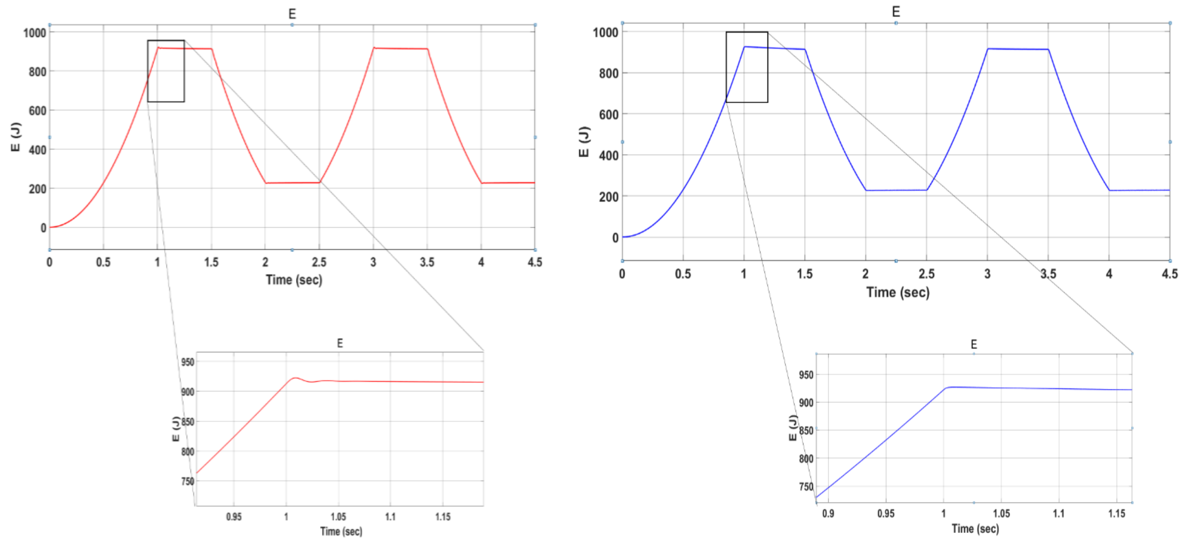


Figure 14. Graph of energy response: (a) back-to-back and (b) matrix converter

4.2.5. Energy response comparison

Observe the grid capacity graph in the period of 3.5-4 s the system is in power discharge mode to push the power to the grid as in Figure 13. When starting the power discharge mode at 3.5 s, it is readily apparent that the matrix converter responds to power immediately, and the back-to-back converter after about 0.014 s responds to power grid. Bidirectional energy exchange between grid and flywheel is done through converters and AFPM, resulting in losses. The performance of the system is harmed by power loss on the converter and AFPM machines. These losses reduce the energy conversion efficiency. They include iron core damage, wire loss and mechanical damage. The energy storage efficiency of the system is:

$$H_{\mathrm{FESS}} = \frac{P_{g\mathrm{rid\_discharge}}}{P_{g\mathrm{rid\_charge}}} 100\% \tag{11}$$

the simulation results show that the performance of the system using matrix converter is higher than back-to-back converters.

5. CONCLUSION

This paper reviews the applied power electronic converters of energy storage technology using flywheel, with focusing on small-grid and utility-grid applications for renewable energy. High speed AFPMs are rated for specific power/density strength, efficiency and open-circuit power loss at high rotational speeds, showing their practicability in FESS with high power density/ private energy opens up opportunities for AFPMs in grid integration of renewable energy. Both converter systems meet the desired speed range of the motor, but the matrix converter system provides a faster power response when changing instantaneous speeds. Simulation results show that this model can be used to study different converter models and control methods to improve energy storage efficiency. Quality improvement issues when using the FESS model can be considered in further studies. Design studies presented in this paper opens up an opportunity for AFPM machines, which is the practice of developing efficient ways to the grid.

REFERENCES

[1] Z. Long and Q. Zhiping, "Review of Flywheel Energy Storage System," in *Proceedings of ISES World Congress 2007 (Vol. I – Vol. V)*, 2008, pp. 2815–2819, doi: 10.1007/978-3-540-75997-3_568.

[2] M. E. Amiryar and K. R. Pullen, "A review of flywheel energy storage system technologies and their applications," *Appl. Sci.*, vol. 7, no. 3, pp. 286, 2017, doi: 10.3390/app7030286.

[3] L. Bakay, M. Dubois, P. Viarouge and J. Ruel, "Losses in hybrid and active magnetic bearings applied to Long Term Flywheel Energy Storage," *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, 2010, pp. 1-6, doi: 10.1049/cp.2010.0067.

[4] J. Feng, W. Gongbao, F. Lijun, W. Gang and X. Zhen, "Applying flywheel energy storage system to integrated power system for power quality and stability enhancement," *2011 International Conference on Electrical Machines and Systems*, 2011, pp. 1-5, doi: 10.1109/ICEMS.2011.6073645.

[5] B. Amel, Z. Soraya, and C. Abdelkader, "Intelligent control of flywheel energy storage system associated with the wind generator for uninterrupted power supply," *Int. J. Power Electron. Drive Syst.*, vol. 11, no. 4, pp. 2062–2072, 2020, doi: 10.11591/ijpeds.v11.i4.pp2062-2072.

[6] T. D. Nguyen, "Dual air-gap axial flux permanent magnet machines for flywheel energy storage systems," Ph.D. dissertation, School of Electrical and Electronic Engineering, Nanyang Technological University, 2012.

[7] M. Bendib, K. Belhouchat and M. Hachemi, "3D finite element analyses and design optimization of AFPM for flywheel energy storage system," *2015 3rd International Conference on Control, Engineering & Information Technology (CEIT)*, 2015, pp. 1-6, doi: 10.1109/CEIT.2015.7233076.

[8] A. Cavagnino, M. Lazzari, F. Profumo and A. Tenconi, "A comparison between the axial flux and the radial flux structures for PM synchronous motors," *Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No.01CH37248)*, 2001, pp. 1611-1618 vol.3, doi: 10.1109/IAS.2001.955750.

[9] M. Aydin, Surong Huang and T. A. Lipo, "Torque quality and comparison of internal and external rotor axial flux surface-magnet disc machines," in *IEEE Transactions on Industrial Electronics*, vol. 53, no. 3, pp. 822-830, June 2006, doi: 10.1109/TIE.2006.874268.

[10] J. F. Gieras, R. J. Wang, and M. J. Kamper, *Axial flux permanent magnet brushless machines*, 2nd ed., Springer Nature: Switzerland, 2005.

[11] A. Credo, M. Tursini, M. Villani, C. Di Lodovico, M. Orlando, and F. Frattari, "Axial flux pm in-wheel motor for electric vehicles: 3d multiphysics analysis," *Energies*, vol. 14, no. 8, pp. 1–18, 2021, doi: 10.3390/en14082107.

[12] K. Sitapati and R. Krishnan, "Performance comparisons of radial and axial field, permanent-magnet, brushless machines," in *IEEE Transactions on Industry Applications*, vol. 37, no. 5, pp. 1219-1226, Sept.-Oct. 2001, doi: 10.1109/28.952495.

[13] J. Santiago, J. G. Oliveira, J. Lundin, A. Larsson and H. Bernhoff, "Losses in axial-flux permanent-magnet coreless flywheel energy storage systems," *2008 18th International Conference on Electrical Machines*, 2008, pp. 1-5, doi: 10.1109/ICELMACH.2008.4800073.

[14] T. Friedli and J. W. Kolar, "Comprehensive comparison of three-phase AC-AC Matrix Converter and Voltage DC-Link Back-to-Back Converter systems," *The 2010 International Power Electronics Conference - ECCE ASIA -*, 2010, pp. 2789-2798, doi: 10.1109/IPEC.2010.5543814.

[15] Trong Duy Nguyen, K. J. Tseng, Shao Zhang and Hoan Thong Nguyen, "On the modeling and control of a novel flywheel energy storage system," *2010 IEEE International Symposium on Industrial Electronics*, 2010, pp. 1395-1401, doi: 10.1109/ISIE.2010.5637797.

[16] M. Nekkaz, A. Djahbar, and R. Taleb, "Modeling and control of two five-phase induction machines connected in series powered by matrix converter," *Int. J. Power Electron. Drive Syst.*, vol. 12, no. 2, pp. 685–694, 2021, doi: 10.11591/ijpeds.v12.i2.pp685-694

[17] B. Wang and G. Venkataramanan, "Dynamic voltage restorer utilizing a matrix converter and flywheel energy storage," *IEEE Trans. Ind. Appl.*, vol. 45, no. 1, pp. 222-231, 2009, doi: 10.1109/TIA.2008.2009507.

[18] J. Zhang, L. Li, D. Dorrell and Y. Guo, "A PI controller with current feedforward to improve the steady-state error performance for a current controlled direct matrix converter," *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, 2017, pp. 1-6, doi: 10.1109/ICEMS.2017.8055961.

[19] B. Vasilev and L. Van Tung, "Research methods of V/F control for matrix converter use direct space vector modulation," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 6, pp. 5115–5124, 2019, doi: 10.11591/ijece.v9i6.pp5115-5124.

[20] K. Selvakumar, R. Palanisamy, A. R. Stalin, P. Gopi, P. Ponselvin, and K. Saravanan, "Simulation of 3-phase matrix converter using space vector modulation," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 2, pp. 909, 2019, doi: 10.11591/ijece.v9i2.pp909-916.

[21] A. K. Sahoo, "Design and Comparison of Passive Component Requirements of a Matrix Converter and Voltage-Source based Back-to-Back Converter," Thesis Dissertation, Faculty of the Graduate School, University of Minnesota, 2013.

[22] M. G. Kesgin, P. Han, N. Taran and D. M. Ionel, "Overview of Flywheel Systems for Renewable Energy Storage with a Design Study for High-speed Axial-flux Permanent-magnet Machines," *2019 8th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2019, pp. 1026-1031, doi: 10.1109/ICRERA47325.2019.8996526.

[23] S. S. K. Budi and M. S. Kumar, "Matrix converter control strategies and modulation techniques," *Int. J. Recent Technol. Eng.*, vol. 8, no. 2 Special Issue 8, pp. 1176–1182, 2019, doi: 10.35940/ijrte.B1033.0882S819.

[24] C. S. Purohit, G. M., P. Sanjeevikumar, P. Kiran Maroti, S. Swami, and V. K. Ramachandaramurthy, "Performance analysis of DC/DC bidirectional converter with sliding mode and pi controller," *Int. J. Power Electron. Drive Syst.*, vol. 10, no. 1, pp. 357, 2019, doi: 10.11591/ijpeds.v10.i1.pp357-365.

[25] P. Yulong, A. Cavagnino, S. Vaschetto, C. Feng and A. Tenconi, "Flywheel energy storage systems for power systems application," *2017 6th International Conference on Clean Electrical Power (ICCEP)*, 2017, pp. 492-501, doi: 10.1109/ICCEP.2017.8004733.

BIOGRAPHIES OF AUTHORS

Nguyen Hung Do received his B.S. and M.S. from Hanoi University of Science and Technology, Vietnam, in 2001, 2008. Currently, he is a PhD student at the Institute of Engineering and Automation - Hanoi University of Science and Technology. His research interests include Electric drive control, Power electronics for applications such as Flywheel energy storage system, Aaxial flux permanent magnet. He can be contacted at email: donguyenhung@gmail.com

Sy Manh Ho was born in 1999. He has studied his B.S. degrees at Hanoi University of Science and Technology in Contron Engineering and Automation. His research interests include power electronics and matrix converter. He can be contacted at email: manh.hs174053@sis.hust.edu.vn.

Quoc Tuan Le was born in 1999. He has studied his B.S. degrees at Hanoi University of Science and Technology in Contron Engineering and Automation. His research interests include power electronics and matrix converter. He can be contacted at email: tuan.lq174325@sis.hust.edu.vn.

Tung Hoang was born in 1999. He has studied his B.S. degrees at Hanoi University of Science and Technology in Contron Engineering and Automation. His research interests include power electronics and matrix converter. He can be contacted at email: tung.hnb174349@sis.hust.edu.vn.

Trong Minh Tran received his B.S. degree Technical University in Bacu, in 1983. He received his M.S. degree from Asian Institute of Technology, Thailand and Ph.D from Hanoi University of Science and Technology, Vietnam, in 2007. His research interests include modelling and controlling of power converters, multilevel converter, HVDC transmission technology. He can be contacted at email: minh.trantrong@hust.edu.vn.

Phuong Vu received his B.S., M.S., and Ph.D. degrees from Hanoi University of Science and Technology, Vietnam, in 2006, 2008, and 2014, respectively, all in Control Engineering and Automation. Since 2006 he has been employed at Hanoi University of Science and Technology, where he is a lecturer and researcher at school of electrical engineering. His research interests include modeling and controlling of power electronics converters for applications such as photovoltaic, wind system, electrical machine drive. He can be contacted at email: phuong.vuhoang@hust.edu.vn.